Journal of Cleaner Production 196 (2018) 1341–1355

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Water saving efficiency and reliability of rainwater harvesting systems in the context of climate change

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ARTICLE INFO

Article history:
Received 15 August 2017
Received in revised form
4 April 2018
Accepted 11 June 2018
Available online 13 June 2018

Keywords:
Rainwater harvesting
Rainfall changes
Water saving efficiency
Reliability

ABSTRACT

Rainwater harvesting (RWH) are receiving notable attention as a promising alternative to address water supply pressures in urban areas. In the context of climate change, however, knowledge about impacts of rainfall changes on RWH is limited. In this study, the impacts of rainfall changes on efficiency and reliability of RWH are investigated at three cities (i.e., Chengdu, Beijing and Urumqi in China). Rainfall change trends are detected using the Mann–Kendall test. A computational tool based on water balance equation is developed and three water demand scenarios (lawn irrigation, toilet flushing, and the combined demand) are considered. The results indicate that the commonly described "dry gets drier, wet gets wetter" rainfall change pattern does not hold in the 57–65 years rainfall records of the three cities. The declining trend of rainfall at both Beijing and Chengdu makes RWH less efficient in water saving and less reliable for meeting water demands, whereas the rising trend of rainfall at Urumqi is favorable for RWH. Rainfall increases in dry season at the three locations are beneficial for RWH while in wet season the impacts are bidirectional depending on the changing trends of rainfall. Impacts of rainfall changes on RWH are dependent on not only trends and extents of rainfall changes, but also tank sizes and water demand scenarios. These findings signify the importance of incorporating rainfall variations in the design and evaluation of RWH systems. Location specific and adaptive measures (e.g., adjusting tank or cistern sizes, contributing areas or water demand scenarios) should be adopted for RWH to accommodate climate change.

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1. Introduction

Water supply systems in many cities are under stresses due to urban development and population growth (Imteaz et al., 2013). With population and economic growth, urban water demand is ever-increasing. On the other side, however, water resources availability is decreasing as a result of water pollution associated with the rapid industrialization and urbanization (Zhao et al., 2013). As reported by United Nation (2013), the world population will reach 9.6 billion by 2050 and about 70% of these population would be living in urban areas. The growing water demand of this huge population would make the naturally limited water resources scarcer (Haque et al., 2014). If no appropriate adaption actions are taken to reinforce water supply systems, about 52% of the global population will probably be exposed to severe water shortages by 2050 (IFPRI, 2012).

Besides the rapid industrialization, urbanization and population growth, changes in climatic conditions are also reported to have essential impacts on water demand and water resources availability (Vorosmarty et al., 2000). The IPCC reports (e.g., IPCC, 2013) on climate change draw attention to the fact that unambiguous detection of global climate change had already occurred. Evaluations of the impacts of climate change on water demand and water resources availability have been made for a number of countries such as the USA (Thompson et al., 2005), UK (Fowler et al., 2007), Iran (Abbaspour et al., 2009), China (Piao et al., 2010), Spain (Majone et al., 2012) and so on. Changes in climatic conditions should be considered in the planning and management of water

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https://doi.org/10.1016/j.jclepro.2018.06.133
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supply systems to guarantee water security and improve resilience of cities in the context of changing environments.

Rainwater harvesting (RWH) is probably the most ancient practice in use to cope with water supply needs (Campisano et al., 2017). Many countries are promoting the implementation of RWH in recent decades to address the increasing water supply pressures associated with social and climatic changes (De Moraes and Rocha, 2013; Amos et al., 2016). In urban areas, it is operated to collect and store rainwater from contributing areas (e.g., building roofs and parking lots) during rainfall events, and store it in tanks or cisterns for use on dry days (Guo and Baetz, 2007; Khastagir and Jayasuriya, 2010). Depending on the quality of harvested rainwater, it can be used to substitute tap water for potable (e.g., drinking and cooking) or non-potable (e.g., toilets flushing, laundry, car washing and garden irrigation) uses (Ghisi et al., 2007; Devkota et al., 2015). Installation of RWH systems can help alleviate urban water supply pressures and increase water self-sufficiency of cities (Godskesen et al., 2013).

Water scarcity and need for water supply augmentation are the primary but not the only reasons that have motivated the wide implementation of RWH systems (Campisano et al., 2017). Environmental benefits such as stormwater management (Palla et al., 2017; Jing et al., 2018) and reduction of emissions with RWH systems (Doménech and Saurí, 2011; Angrill et al., 2012; Morales-Pinzón et al., 2015; An et al., 2015; Ghimire et al., 2017) have been extensively explored in recent years. While, reliability and water saving of RWH systems are still the most concerned objectives in many studies (Imteaz et al., 2013; Mehrabadi et al., 2013; Karim et al., 2015).

Water saving and reliability of RHW systems are fundamentally related to site conditions such as climate and catchment (Mehrabadi et al., 2013; Imteaz et al., 2013), the storage size (Khastagir and Jayasuriya, 2010; Sample and Liu, 2014), and the water demand scenarios (Ward et al., 2012). Therefore, design of a RWH system needs to incorporate anticipated water demands that align with the local rainfall patterns and catchment conditions to substantially increase the overall multi-objective efficiency of the system (Zhang et al., 2009; Campisano et al., 2017).

The range of applications of RWH systems in urbanized areas is very large. However, the results and the perception of the extent of potential benefits are varied (Campisano et al., 2017). Various approaches can be used in RWH systems design, optimization, and performance evaluation, for instance, the design storm approach (Vaes and Berlamont, 2001), continuous simulations (Jenkins, 2007), the analytical probabilistic approach (Guo and Baetz, 2007), the stochastic approach (Unami et al., 2015), linear programming approach (Okoye et al., 2015), the nonlinear metaheuristic algorithm (Sample and Liu, 2014), and the dimensionless methodology (Campisano and Modica, 2012). Among these approaches, long-term continuous simulations based on water balance theory are the most frequently applied to optimize the size of RWH systems (Hashim et al., 2013) and to analyze the water saving and/or stormwater management performances (Hajani and Rahman, 2014; Jing et al., 2018).

In the design, optimization, and performance evaluation of RWH systems, local rainfall is the main variable of interest (Campisano et al., 2017), as it largely determines the volume of collectible rainwater. Most of previous studies were based on historical rainfall data and making an average of cumulative historical water savings, reliabilities, and other model variables to perform the design, optimization or evaluation. However, RWH users may not get an adequate insight of the expected realistic situations regarding variability of the outputs through such analysis of averaged variables/parameters (Imteaz et al., 2013). In the context of climate change, such ranges of uncertain outcomes are expected to be widen further.

Only a few studies incorporated future rainfall data downscaled from Global Climate Models (GCMs) predicted products in the evaluations of RWH systems. For example, Lo and Koralegedara (2015) used rainfall data downscaled from GCMs to assess the effects of climate change on urban RWH in Colombo city. Wallace et al. (2015) incorporated downscaled rainfall data from GCMs in developing design curves for varying levels of reliability of RWH systems in the Federated States of Micronesia. Haque et al. (2016) investigated the impacts of rainfall changes on RWH systems in the Greater Sydney region. These pioneering researches have revealed the importance of incorporating rainfall changes in RWH system design and evaluation. However, research on climate change impacts on rainwater harvesting is still limited as the trends and extents of climate change vary considerably from region to region (IPCC, 2013). Besides using predicted future rainfall date downscaled from GCMs with inherent uncertainties, long-term historical rainfall data can also be used to explore the impacts of climate change on RWH. Moreover, using long-term historical records of rainfall is expected to reveal more realistic impacts of climate change than synthetic uncertain rainfall data downscaled from GCMs.

The novelty of this study is to use long-term (57–65 years) historical rainfall data to explore climate change impacts on RWH in cities which have experienced different trends and extents of rainfall variations. Three cities (i.e., Chengdu, Beijing, and Urumqi) located in different climatic zones of China are selected. The trends and extents of annual, dry season and wet season rainfall of them are detected using the Mann–Kendall test. The impacts of rainfall variations on water savings and reliability of RWH systems in the three cities are evaluated using a daily water balance model which is developed by taking daily rainfall data, contributing roof area, rainfall loss factors, design storage capacity, and daily rainwater usage rate into consideration. Three water demand scenarios (lawn irrigation, toilet flushing, and a combined demand) are included in the evaluation.

2. Study area and data

As shown in Fig. 1, three cities located in different climatic zones of China are selected in this study, namely Chengdu (humid climate), Beijing (semi-humid climate), and Urumqi (semi-arid climate). Historical daily rainfall data of the three cities are obtained from the National Climatic Centre (NCC) of China. Length of the historical rainfall data ranges from 57 to 65 years and the mean annual rainfall volume ranges from 273.0 mm in Urumqi, 587.2 mm in Beijing, to 919.4 mm in Chengdu (Table 1). Average monthly rainfall varies quite a lot, especially for Beijing and Chengdu which are both located in monsoon areas (Table 1). Based on the mean monthly rainfall, wet and dry seasons can be distinguished for the three cities. Wet season of Chengdu is from March to August, and that of Beijing is from May to October. For Urumqi, it is from April to September. Average rainfall in wet season accounts for 88.0%, 91.2% and 65.4% of the mean annual rainfall at Chengdu, Beijing and Urumqi, respectively.

The most common building form in those cities is multi-storey buildings with relatively flat roofs. And most of the buildings are surrounded by green spaces planted with grasses or trees. In this study, the roof area of the building is 1000 m^2 and it serves about 100 inhabitants. The area of the surrounding green spaces of this building is 4000 m^2. Rainwater generated from the building roof, after bypassing first flush, can be collected and used for indoor uses such as flushing toilets or urinals, or outdoor uses such as green space irrigation.

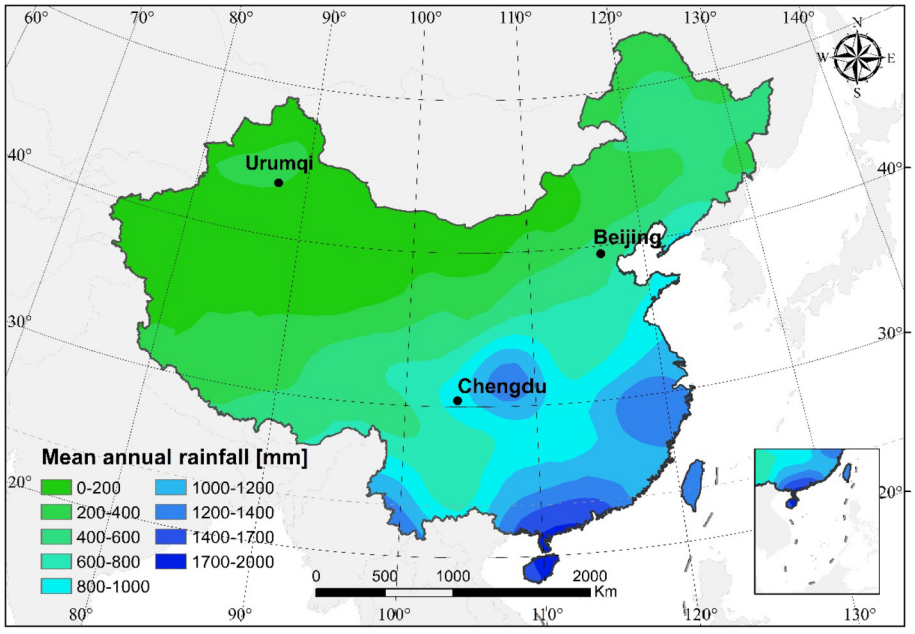

Fig. 1. Spatial distribution of mean annual rainfall of China and locations of the three cities. [modified from Jing et al. (2017)].

Table 1
Length of data, mean annual and monthly rainfall of Chengdu, Beijing and Urumqi.

Cities	Length of data	Mean annual rainfall (mm)	Mean monthly rainfall (mm)											
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Chengdu	1959–2015	919.4	22.3	39.3	75.5	101.2	217.6	215.6	148.3	50.7	21.2	7.8	7.8	12.2
Beijing	1951–2015	587.2	2.7	5.9	9.1	22.3	34.7	75.7	178.7	169.2	54.3	22.7	9.5	2.3
Urumqi	1951–2015	273.0	9.3	10.8	19.4	33.4	34.2	33.6	28.7	23.7	23.3	22.8	19.0	14.8

3. Methodology

3.1. Daily water balance model

A daily water balance model is developed to simulate the inflow (runoff generated from contributing areas), outflow (desired rainwater for non-potable uses), and overflow (first flush and excess rainwater directed into drainage systems) of RWH systems. The inflow (I_t) can be determined as

$$I_t = \begin{cases} 0, & H_t \le \delta \\ \dfrac{\psi(H_t - \delta)F}{1000}, & H_t > \delta \end{cases} \quad (1)$$

where I_t is the collectable runoff generated from the contributing areas (after bypassing first flush) on the t th day, in m^3; H_t is the volume of rainfall on the t th day, in mm; ψ is the runoff coefficient of the contributing areas, dimensionless; F is the area of the contributing areas, in m^2; δ is the volume of first flush over the area of the contributing area, in mm. As suggested by previous studies (Guo and Baetz, 2007; Kus et al., 2010), a first flush depth of 2 mm (i.e., $\delta = 2$ mm) is usually diverted away from the rainwater storage units to improve quality of harvested rainwater. A 10% deduction is usually applied to account for losses of rainwater resulting from leakage, spillage and evaporation of a rooftop RWH system (Imteaz et al., 2013; Sample and Liu, 2014; Okoye et al., 2015; Liuzzo et al., 2016). Thus, the runoff coefficient of rooftops is set as 0.9 in this study (i.e., $\psi = 0.9$). However, for real case studies, the values of both δ and ψ should be varying with specific conditions such as local climate, air quality, materials of rooftops, and types of rainwater collecting systems.

Basic modelling approaches of "yield after spillage" (YAS) and "yield before spillage" (YBS) (Fewkes and Butler, 2000) have been used in many studies on RWH systems. General conclusions support the use of the YAS operating algorithm for design purposes as it results in a more conservative estimate of water saving efficiency (Liaw and Tsai, 2004; Mitchell, 2007). Applying the YAS operating rule, rainwater yield from a RWH system can be calculated as

$$Y_t = \begin{cases} R_{t-1} + I_t, & R_{t-1} + I_t - D_t \le 0 \\ D_t, & R_{t-1} + I_t - D_t > 0 \end{cases} \quad (2)$$

$$R_t = \begin{cases} R_{t-1} + I_t - Y_t, & R_{t-1} + I_t - S_c \le 0 \\ S_c - Y_t, & R_{t-1} + I_t - S_c > 0 \end{cases} \quad (3)$$

where Y_t is the volume of rainwater yield on the t th day, in m^3; D_t is the water demand on the t th day, in m^3; R_t is the volume of rainwater remained in the RWH storage unit at the end of the t th day, in m^3; S_c is the designed storage capacity of the RWH storage unit, in m^3.

The efficiency of the RWH system for reducing urban water supply stress can be evaluated by water saving efficiency (w , %), which is calculated as,

$$W = \frac{\sum Y_t}{\sum D_t} \times 100\% \quad (4)$$

Time reliability of water supply of the RWH system is expressed as follows,

$$g = \frac{N-U}{N} \times 100\% \quad (5)$$

where U is the number of days in total the RWH system is unable to meet the water demand (i.e., $R_{t-1} + I_t < D_t$), and N is the total number of days of the simulation period.

3.2. Mann–Kendall test

The Mann–Kendall method, which was originally devised by Mann (1945) as a non-parametric test for detecting trends and the distribution of the test statistic, derived by Kendall (1975), is used to test the trends of the annual, dry and wet seasonal rainfall series.

Let x_1, x_2, …, x_n be the data points. For each element x_i, the numbers n_i of elements x_j preceding it (j < i) such that $x_j < x_i$ are computed. Under the null hypothesis (no trend), the test statistic (t_k) is normally distributed with mean and variance given by

$$t_k = \sum_{i=1}^{i=k} n_i \quad (6)$$

$$E(t_k) = \frac{k(k-1)}{4} \quad (7)$$

$$Var(t_k) = \frac{k(k-1)(2k+5)}{72} \quad (8)$$

Let

$$U_k = \frac{t_k - E(t_k)}{\sqrt{Var(t_k)}} \quad (9)$$

be the normalized variable. When the null hypothesis is rejected (i.e. if any of the points in the sequence are outside the confidence intervals), the detection of an increasing (U_k>0) or a decreasing (U_k < 0) trend is indicated. The 5% significance level intervals for U_k are ±1.96, and the 1% significance level intervals are ±2.58.

3.3. Water demand scenarios

In this study, three non-potable water demand scenarios are assessed. They are (1) lawn irrigation, (2) toilet flushing, and (3) combined demand (lawn irrigation + toilet flushing). According to the Code for Design of Stormwater Management and Harvest Engineering (DB11/685–2013), toilet flushing water demand for a multi-storey residential building is 32 L per person per day. The daily toilet flushing water demand for the building can be estimated as 100 person × 32 L per person per day, which is 3.2 m^3/day.

The frequency and quota of lawn irrigation depends on types of grass, soil properties and climatic conditions. In order to estimate the irrigation demand of the lawns, mean monthly reference evapotranspiration values of the 3 locations were determined using the CROPWAT 8.0 software (Allen et al., 1998). Table 2 shows the monthly irrigation frequency and quota for turfgrass lawns located in each of the 3 cities. Details about the calculation procedures can be found in Jing et al. (2017)..

4. Results and discussions

4.1. Changes in annual and seasonal rainfall

In the past 57–65 years, Chengdu, Beijing and Urumqi had experienced different trends and extents of changes in rainfall. From the annual rainfall fluctuations (Fig. 2), it can be notably seen that the annual rainfall at Beijing shows a decreasing trend while that of Urumqi seems to be increasing. Among the three cities, Beijing has the most variable annual rainfall with a coefficient of variation (C_V) value of 0.35 (n = 65) and the highest annual rainfall at Beijing is 1406.0 mm, which is five times higher than the lowest. The C_V value of annual rainfall at Urumqi is 0.27 (n = 65). The annual rainfall at Chengdu varies the least with a C_V value of 0.20 (n = 57), and its highest annual rainfall is 1423.9 mm, which is only twice higher than the lowest.

Taking the millennium as the dividing point, the annual and seasonal rainfall records of the three cities can all be divided into two parts: a baseline period (1951–1999 for Beijing and Urumqi, and 1959–1999 for Chengdu) and a changed period (2000–2015). Changes of average annual and seasonal rainfall between the baseline and changed periods are presented in Table 3. Among the three cities, Beijing had faced the highest reduction in both average annual and wet seasonal rainfall (−22.3% and −26.1%, respectively), whereas the average annual and wet seasonal rainfall in Urumqi had increased 20.3% and 15.0%, respectively. Chengdu also experienced relatively slight decreases in both average annual and wet seasonal rainfall (−7.6% and −9.9%, respectively). Although the trends of annual and wet seasonal rainfall were different among the three cities, average rainfall in dry season of them had all increased, by 10.1%–30.3%.

The Mann–Kendal method is applied to test the trends of the annual and seasonal rainfall series. With the 57–65 years annual, dry and wet seasonal rainfall series of the three cities as input, the U_k values for detecting the changing trends of the annual, dry and wet seasonal rainfall series are calculated using Eq. (9) and shown in Fig. 3. The decreasing trends of annual and wet seasonal rainfall

Table 2
Irrigation frequency and quota of lawns at Chengdu, Beijing and Urumqi.

Month	Chengdu		Beijing		Urumqi	
	Irrigation Frequency	Average Daily Quota (m^3/d)	Irrigation Frequency	Average Daily Quota (m^3/d)	Irrigation Frequency	Average Daily Quota (m^3/d)
Jan	None	0	None	0	None	0
Feb	None	0	None	0	None	0
Mar	Fortnightly	0.36	Fortnightly	0.62	Monthly	0.14
Apr	Fortnightly	0.50	Every 5 days	3.16	Fortnightly	0.80
May	Weekly	1.26	Every 3 days	4.42	Every 3 days	4.08
Jun	Every 3 days	2.42	Every 3 days	4.80	Every 2 days	7.08
Jul	Every 3 days	2.48	Every 3 days	3.80	Every 2 days	7.18
Aug	Every 3 days	2.52	Every 5 days	2.86	Every 2 days	6.96
Sept	Weekly	1.06	Weekly	1.80	Every 5 days	3.04
Oct	Fortnightly	0.34	Fortnightly	0.62	Monthly	0.34
Nov	None	0	None	0	None	0
Dec	None	0	None	0	None	0

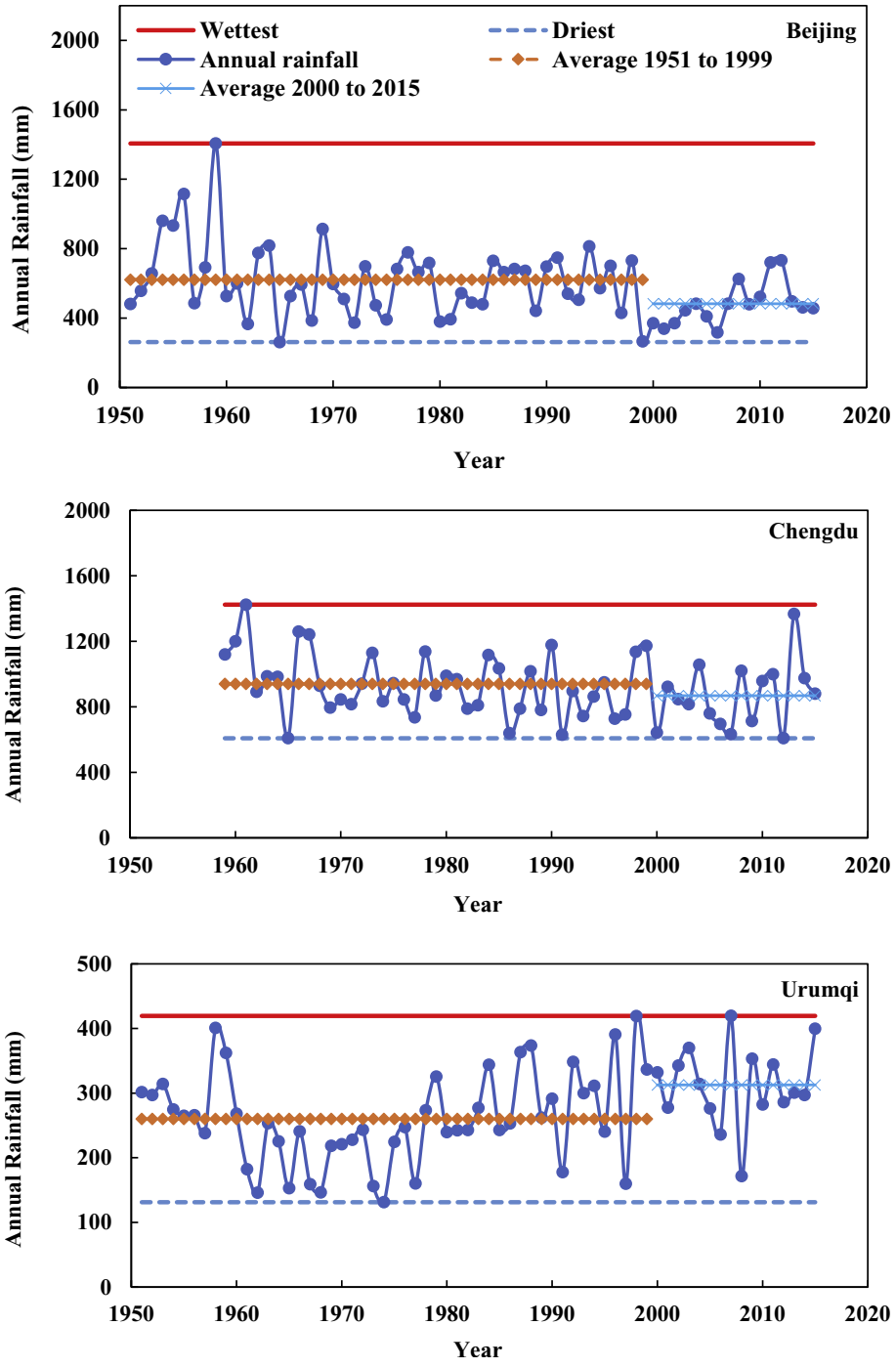

Fig. 2. Annual rainfall of Beijing, Chengdu and Urumqi.

Table 3
Changes in annual and seasonal average rainfall at Beijing, Chengdu and Urumqi.

Cities	Annual			Wet season			Dry season		
	Baseline period	Changed period	Changes	Baseline period	Changed period	Changes	Baseline period	Changed period	Changes
Chengdu	939.4	868.2	**−7.6%**	831.8	749.8	**−9.9%**	107.6	118.4	**10.1%**
Beijing	621.4	482.6	**−22.3%**	572.2	422.7	**−26.1%**	49.2	59.8	**21.6%**
Urumqi	260.0	312.8	**20.3%**	170.6	196.2	**15.0%**	89.4	116.5	**30.3%**

Note: changes in % are the relative differences between average rainfall in the changed and baseline periods.

at Beijing are both significant at the confidence level of 95%, whereas the annual and wet seasonal rainfall at Urumqi both shows extremely significant rising trends at the confidence level of 99%. In Chengdu, the decreasing trend of rainfall in wet season passes the

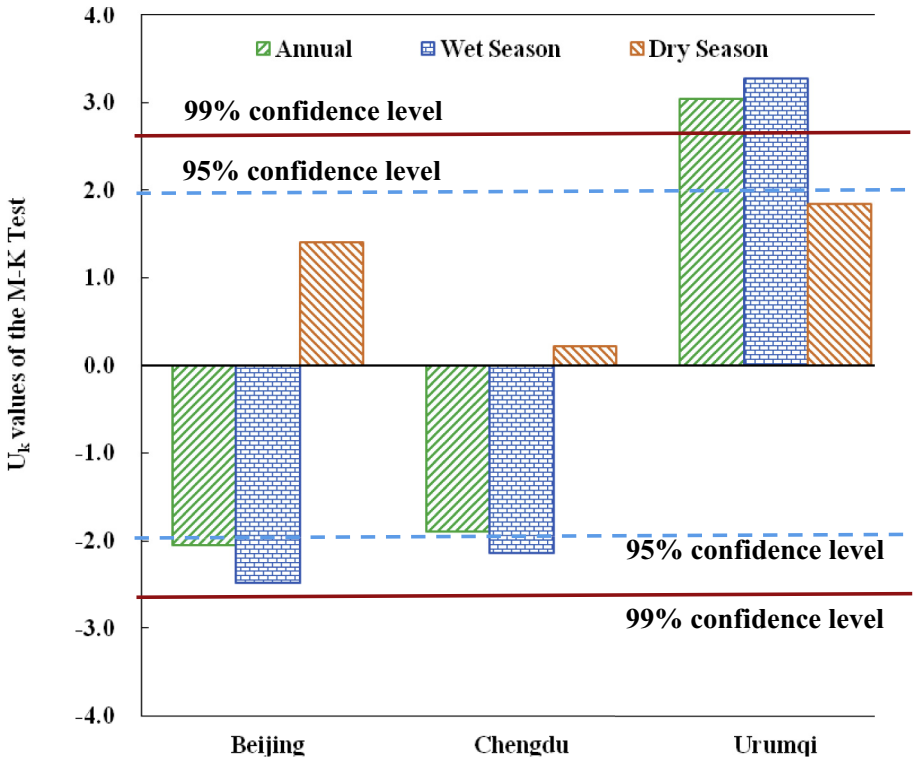

Fig. 3. Mann–Kendall tests of annual and seasonal rainfall at Beijing, Chengdu and Urumqi.

test at the confidence level of 95%, while the decreasing in annual rainfall is non-significant at this confidence level. Although rainfall in dry season shows an increasing trend for all the three cities, the trend could not pass the test at the confidence level of 95%.

Under climate change, a trend towards more uneven distribution of precipitation has been detected both spatially (Held and Soden, 2006; Chou et al., 2009) and temporally (Chou et al., 2013) at the global scale. The pattern of the trend towards more uneven distribution of rainfall is commonly described by the phrase "dry gets drier, wet gets wetter" (Chen et al., 2017). The study of Haque et al. (2016) supports this rainfall changing pattern as it reports that the dry season is expected to be drier while the wet season would be wetter in future at the Sydney region. However, the "dry gets drier, wet gets wetter" pattern does not hold in the analysis of historical rainfall records in Beijing, Chengdu or Urumqi. The almost totally contradictory rainfall change patterns at the three cities signify that impacts of climate change on RWH at locations with different climate change patterns should be evaluated respectively, and location specific and adaptive measures should be taken to improve the water saving efficiency and reliability of RWH systems in the context of climate change.

4.2. Impacts of rainfall changes on water saving efficiency

Impacts of rainfall changes on water saving efficiency of RWH systems with storage capacity varying from 1 to 1000 m^3 for the three water demand scenarios at Beijing, Chengdu and Urumqi are presented in Figs. 4–6, respectively. At Beijing (Fig. 4), water saving efficiencies of RWH systems with any storage capacity (1–1000 m^3) and for all the three water demand scenarios are always lower in the changed period (2000–2015) than that in the baseline period (1951–1999). This is interrelated to the significant reduction of annual rainfall (−22.3%) occurred in Beijing as earlier mentioned. It indicates that the reduction in rainfall at Beijing makes RWH systems less efficient in water saving.

As shown in Fig. 4, the changes of water saving efficiency of RWH systems between the changed and baseline periods decrease firstly as the storage capacity of the systems increases from 1 m^3 to threshold values (10–50 m^3 depending on the water demand scenarios), and then get lager and lager when the storage capacity increases from the threshold values to about 800 m^3. As the storage capacity goes beyond 800 m^3, the changes of water saving efficiency stay at constant values around 32.0% for all the three water demand scenarios. Reasons for the flexuous variations of the changes in water saving efficiency with storage capacity are complicated.

First, when the storage capacity of RWH systems is relatively small (e.g., less than 10–50 m^3 in these cases), the limiting factor for the water saving performances of the systems is the storage capacity. Under this circumstance, increasing the storage capacity of a RWH system could enhance its water saving performances and reinforce its resilience to climate change. However, when the storage capacity of RWH systems increases beyond the threshold values, the limiting factor of the water saving performances of the systems changes into local rainfall conditions. The drier the climate is, the smaller the threshold value could be. The changed period with an average annual rainfall of 482.6 mm is drier than the baseline period with an average annual rainfall of 621.4 mm. Therefore, the water saving efficiency of RWH systems increases more moderately with the storage capacity in the changed period than in the baseline period when the storage capacity exceeds the threshold values for the changed period. This is likely to be the reason why the changes of water saving efficiency increase with storage capacity when it exceeds the threshold values. When the storage capacity exceeds about 800 m^3, the water saving efficiency of RWH systems keeps at constant levels for both the changed and baseline periods, as a result, the changes between the water saving efficiency for these two periods also stay at constant values.

Fig. 5 shows the impacts of rainfall changes on water saving efficiency of RWH systems at Chengdu. The differences between

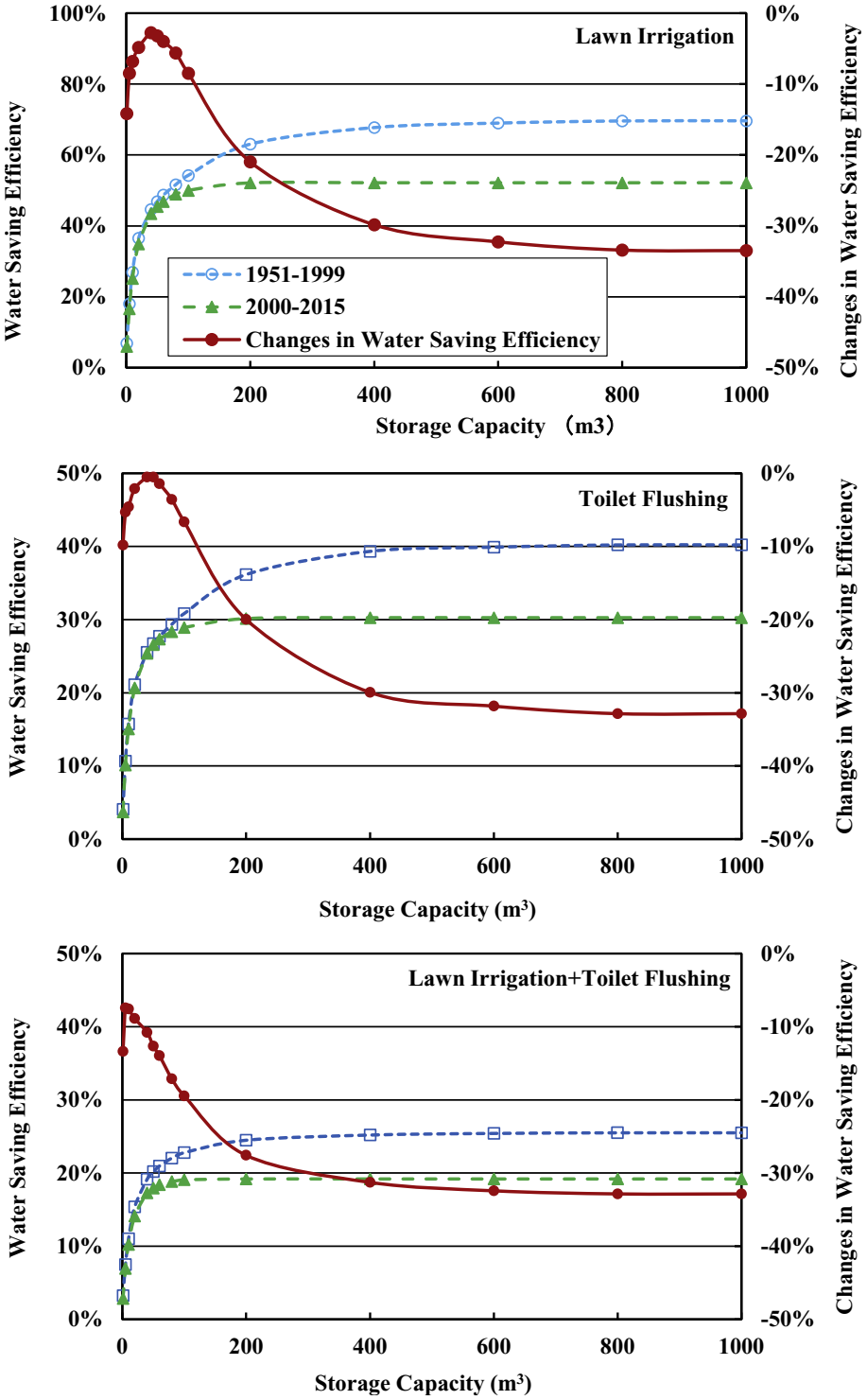

Fig. 4. Changes in water saving efficiency at Beijing.

water saving efficiency in the changed and baseline periods are dependent on water scenarios. This is likely to be interrelated with the non-significant changing trend of annual rainfall at Chengdu as stated earlier. For lawn irrigation (0–2.52 m^3/day varying from month to month), water saving efficiencies of RWH systems in the changed and baseline periods are almost the same, especially when the storage capacity is larger than 80 m^3. However, for toilet flushing (3.20 m^3/day) and the combined demand (3.20–5.72 m^3/day varying from month to month), water saving efficiency of RWH systems is always lower in the changed period than that in the baseline period. It indicates that, in terms of water saving efficiency, the rainfall change at Chengdu has negative impacts on RWH for toilet flushing and the combined demand, but does not have notable impacts on RWH for lawn irrigation.

The impacts of rainfall changes on water saving efficiency of RWH systems at Urumqi is presented in Fig. 6. It is notable that water saving efficiency for RWH systems with any storage capacity and for all of the three water demand scenarios is always higher in

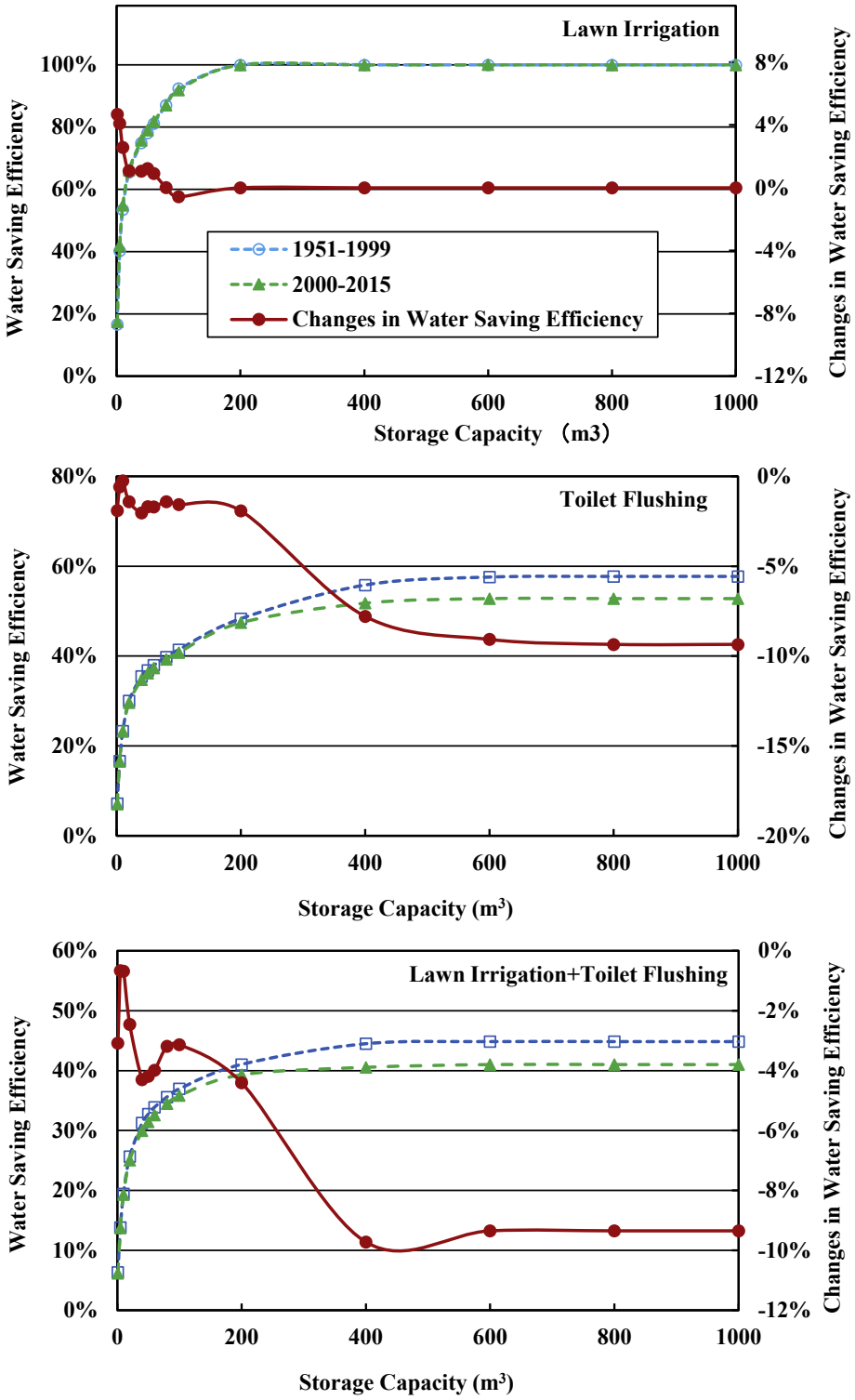

Fig. 5. Changes in water saving efficiency at Chengdu.

the changed period than that in the baseline period. It is because the average annual rainfall at Urumqi had significantly increased (20.3%) in the changed period. The changes of water saving efficiency of RWH systems firstly increase as the storage capacity of the systems increases from 1 m^3 to threshold values (40–100 m^3 depending on the water demand scenarios), and then keep at constant values around 22.7% for all the three water demand scenarios. This indicate that the rainfall change at Urumqi is beneficial for RWH as it lifts the upper limit of the water saving efficiencies for all the three water demand scenarios.

Impacts of rainfall changes in wet and dry seasons on water saving efficiency of RWH systems with storage capacity of 100 m^3 for the three water demand scenarios are presented in Fig. 7. In wet season, water saving efficiency of RWH is decreasing at both Beijing

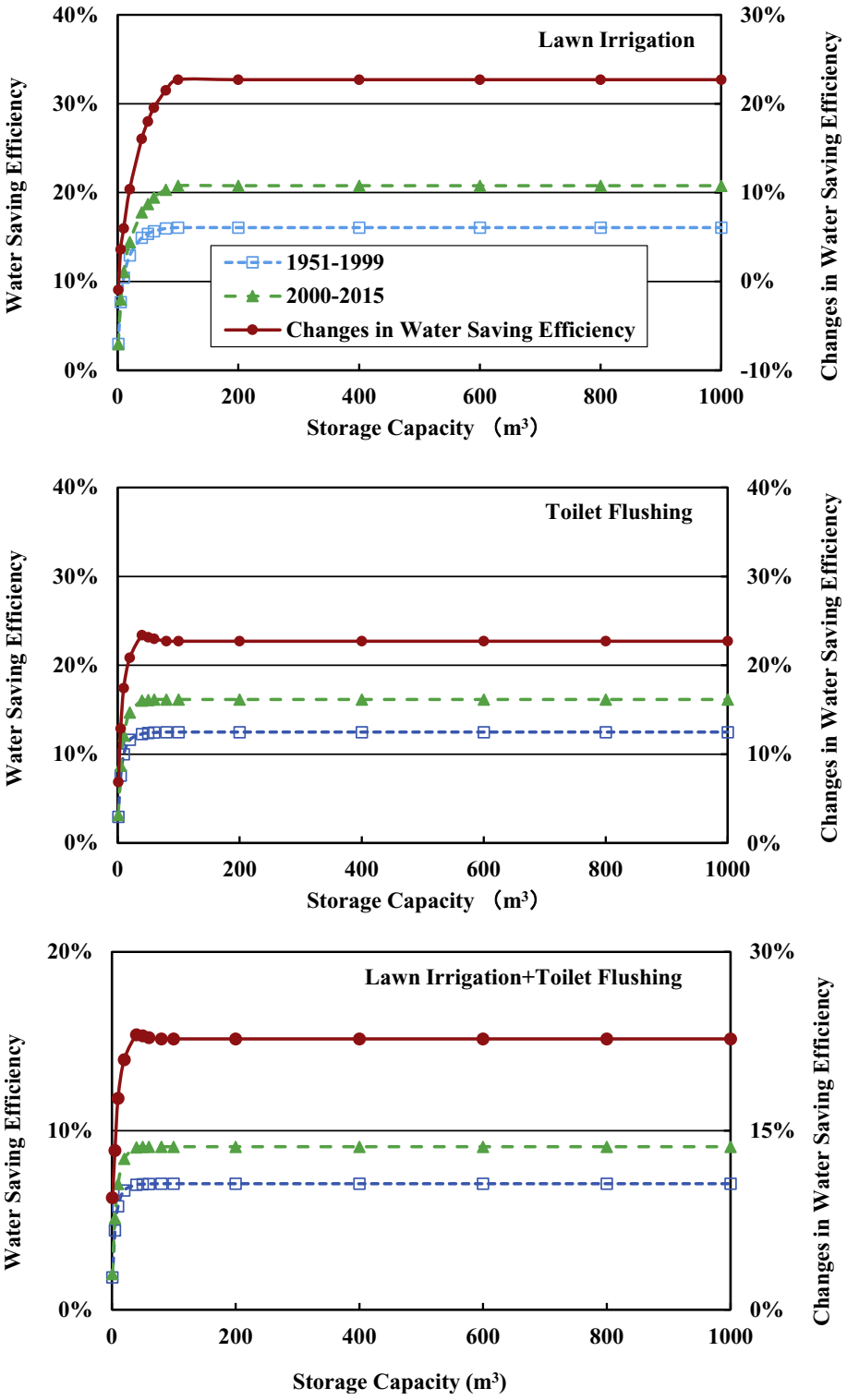

Fig. 6. Changes in water saving efficiency at Urumqi.

and Chengdu, but increasing at Urumqi for all the three water demand scenarios. This is in line with the different trends of rainfall change in wet season at the three locations: decreasing at Beijing and Chengdu (−26.1% and −9.9%, respectively) and increasing at Urumqi (15.0%) as presented in Table 3. As all the three cities are getting more rainfall in dry season, the water saving efficiencies of RWH systems at all of them are rising in dry season. Depending on water demand scenarios and locations, the water saving efficiencies in dry season have gone up at different extents from 3.7% to 47.1%. The seasonal changes in water saving efficiencies at the three locations indicate that the rainfall change in dry season is beneficial for RWH whereas the impacts of rainfall change in wet season on RWH are bidirectional at the three locations depending on the changing trends of rainfall.

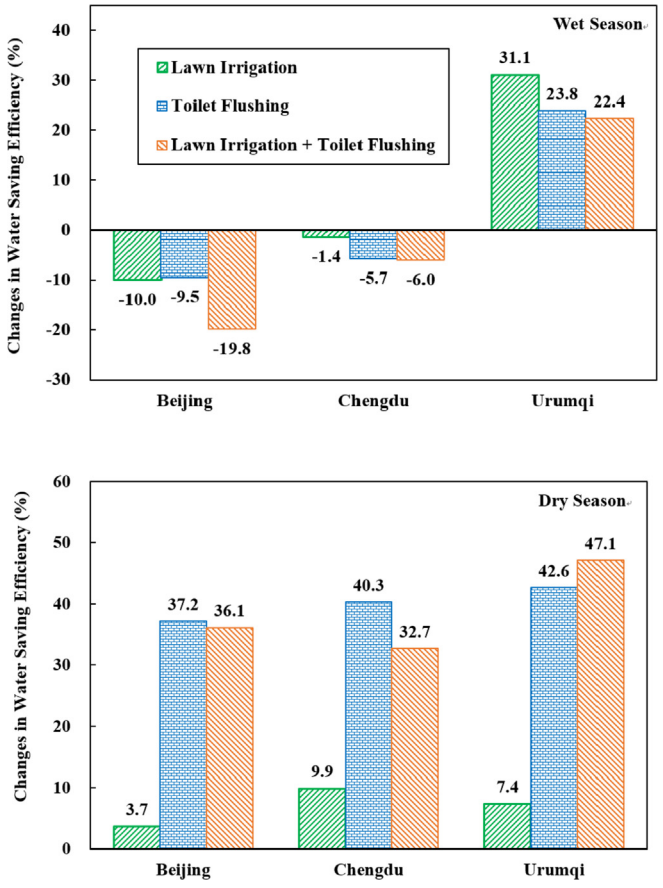

Fig. 7. Impacts of seasonal rainfall changes on water saving efficiency.

4.3. Impacts of rainfall changes on reliability of RWH systems

Impacts of rainfall changes on reliability of RWH systems with storage capacity varying from 1 to 1000 m^3 at Beijing, Chengdu and Urumqi are presented in Figs. 8–10, respectively. Reliability of RWH systems at Beijing (Fig. 8) declined in the changed period in comparing with the baseline period in the vast majority of cases except when the harvested rainwater is used for lawn irrigation and the storage capacity is between 5 and 40 m^3. The decline in reliability is mainly attributed to the reduction of rainfall in the changed period as compared with the baseline period. The reliability of RWH systems for all the three water demand scenarios increases with the storage capacity until certain storage sizes, about 200 m^3 for the changed period and 800 m^3 for the baseline period, beyond which reliability cannot be improved by increase the storage capacity. This indicates that the decline in the maximum (or achievable) reliability of RWH in the changed period for different water demand scenarios could not be simply resolved by using a larger tank or cistern. The achievable reliabilities of RWH systems are different dependent on the water demand scenarios and rainfall conditions. The achievable reliabilities of RWH systems for lawn irrigation, toilet flushingand the combined demand in the changed period at Beijing are 73.2%, 27.9%, and 13.3%, respectively, which are 15.4%, 37.9%, and 47.3% lower than the corresponding ones in the baseline period. The larger the water demand, the severer the decline in the achievable reliability. It reveals that the reduction of rainfall at Beijing has more negative impacts on RWH for larger water demand scenarios in terms of reliability.

Fig. 9 shows the impacts of rainfall changes on reliability of RWH systems at Chengdu. As the slight reduction of annual rainfall (−7.6%) is not significant, the differences between reliability of RWH systems in the changed and baseline periods are dependent on water scenarios. For lawn irrigation, the reliability of RWH systems in the changed and baseline periods are almost the same with relatively small changes ranging from −0.13% to 1.64%, whereas the changing ranges of the reliability of RWH systems for the other two water demand scenarios are larger (−10.2%–0.2%). The maximum achievable reliabilities of RWH systems for lawn irrigation, toilet flushing and the combined demand in the changed period at Chengdu are 100%, 50.5%, and 32.5%, respectively, and that in the baseline period are 100%, 55.3%, and 35.4%, respectively. The decreases in reliability of RWH at Chengdu is less as compared with that in Beijing. This is in accordance with the extents of reduction in annual rainfall at the two locations: −7.6% in Chengdu versus −22.3% in Beijing.

At Urumqi, changes in reliability of RWH systems are positive for all the storage capacity (1–1000 m^3) and all the water demand scenarios (Fig. 10). The curves of reliability of RWH systems for the changed period are above the ones for the baseline period. It means that the increasing trend of annual rainfall at Urumqi could evidently improve the reliability of RWH systems. Depending on the water demand scenarios, the relative changes of reliability of RWH systems increase with the storage capacity firstly and then keep at constant values ranging from 5.7% to 35.8%. Through rainfall changes in the past several decades favorite RWH systems in Urumqi and the relative changes in reliability of RWH systems could reach 35.8% for the combined demand, it should be noted that the maximum achievable reliability for this scenario is only 6.8%.

Impacts of rainfall changes in wet and dry seasons on reliability of RWH systems with storage capacity of 100 m^3 are presented in Table 4. For all the three locations, reliability is found to be less in dry season than that of wet season as rainfall at the locations is much smaller in the dry season compared to wet season. In wet season, reliability of RWH is decreasing at both Beijing and Chengdu (−1.1% to −24.0%), but increasing at Urumqi (23.1%–44.9%) for all the three water demand scenarios. This is in line with the different trends of rainfall change in wet season at the three locations (Table 3). As all the three cities are getting more rainfall in dry season, the reliability of RWH systems at all of them are rising in dry season. Depending on water demand scenarios and locations, the reliability in dry season have gone up at different extents from 1.1%% to 80.4%.

5. Summary and conclusions

Rainwater harvesting (RWH) has been receiving notable attention as an alternative solution to address water supply pressures and stormwater management problems in urban areas. However, in the context of climate change, research on impacts of rainfall changes on efficiency and reliability of RWH systems is limited. In this study, the impacts of rainfall changes on water saving efficiency and reliability of RWH systems are investigated at three cities (i.e., Chengdu, Beijing and Urumqi in China) which have experienced different trends and extents of annual and seasonal rainfall changes in the past 57–65 years. A computational tool based on water balance equation and the YAS (yield after spillage) operating rule is developed to assess the impacts. Three water demand scenarios (lawn irrigation, toilet flushing, and the combined demand) are evaluated.

The commonly described “dry gets drier, wet gets wetter” rainfall change pattern does not hold in the 57–65 years historical rainfall records of Chengdu, Beijing, or Urumqi. Annual rainfall has significantly increased at the 99% confidence level at semi-arid Urumqi and decreased at semi-humid Beijing (significantly at the

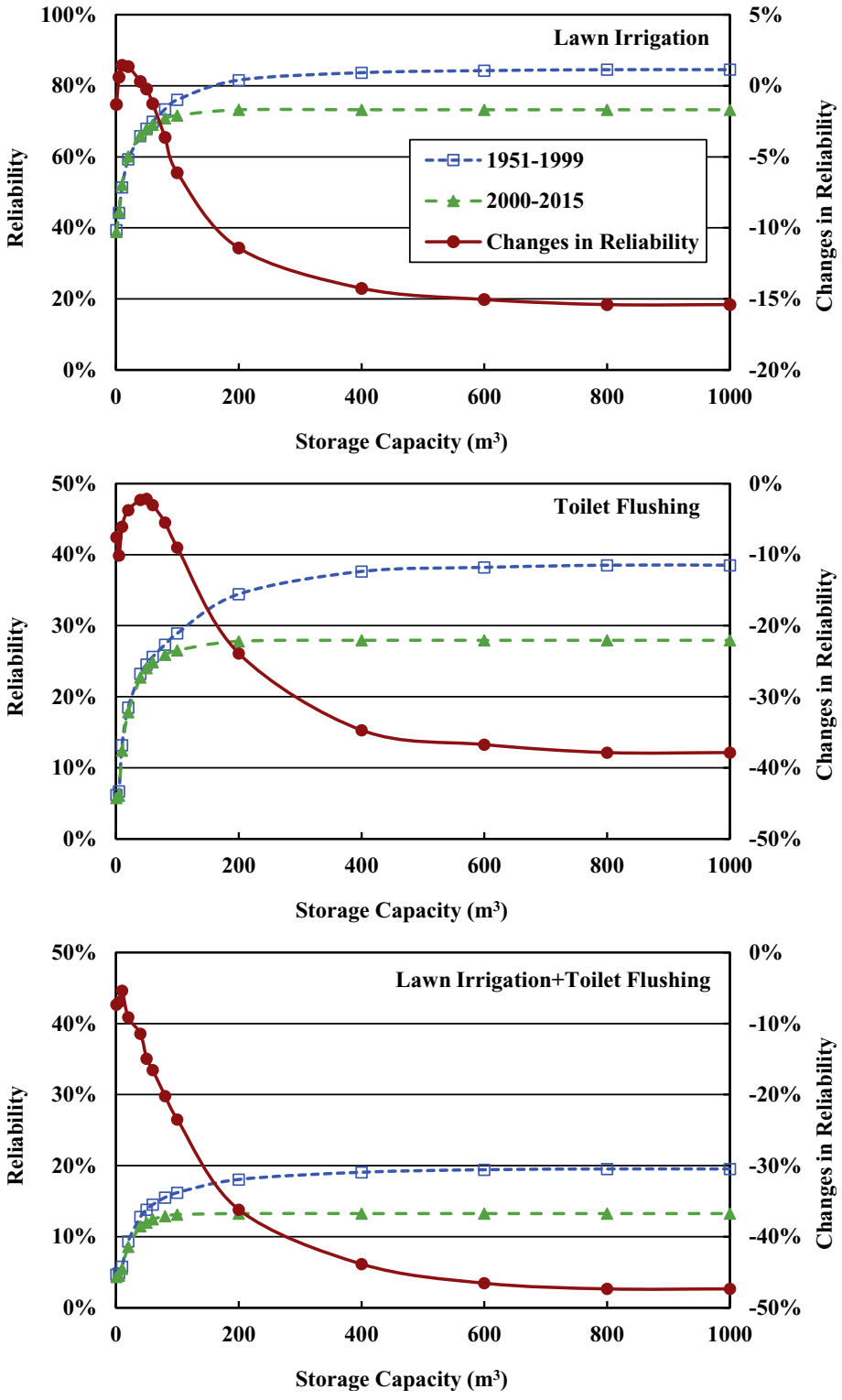

Fig. 8. Changes in reliability of RWH systems at Beijing.

95% confidence level) and humid Chengdu (non-significantly at the 95% confidence level). Dry season got wetter (increased rainfall) for all of the three locations, and the rainfall in wet season decreased significantly at the 95% confidence level for both Beijing and Chengdu and increased significantly at the 99% confidence level for Urumqi.

Water saving efficiency of RWH systems can be positively or negatively influenced by, correspondingly, increases or decreases in rainfall. Water saving efficiency of RWH at Beijing are decreasing due to the significant reduction in rainfall, whereas the rising trend of rainfall at Urumqi is beneficial for RWH. At Beijing, the maximum water saving efficiencies of RWH for the three water demand scenarios in the changed period (2000–2015) are 69.6%, 40.2%, and 25.5%, respectively, which are 33.5%, 32.9%, and 32.9% lower than

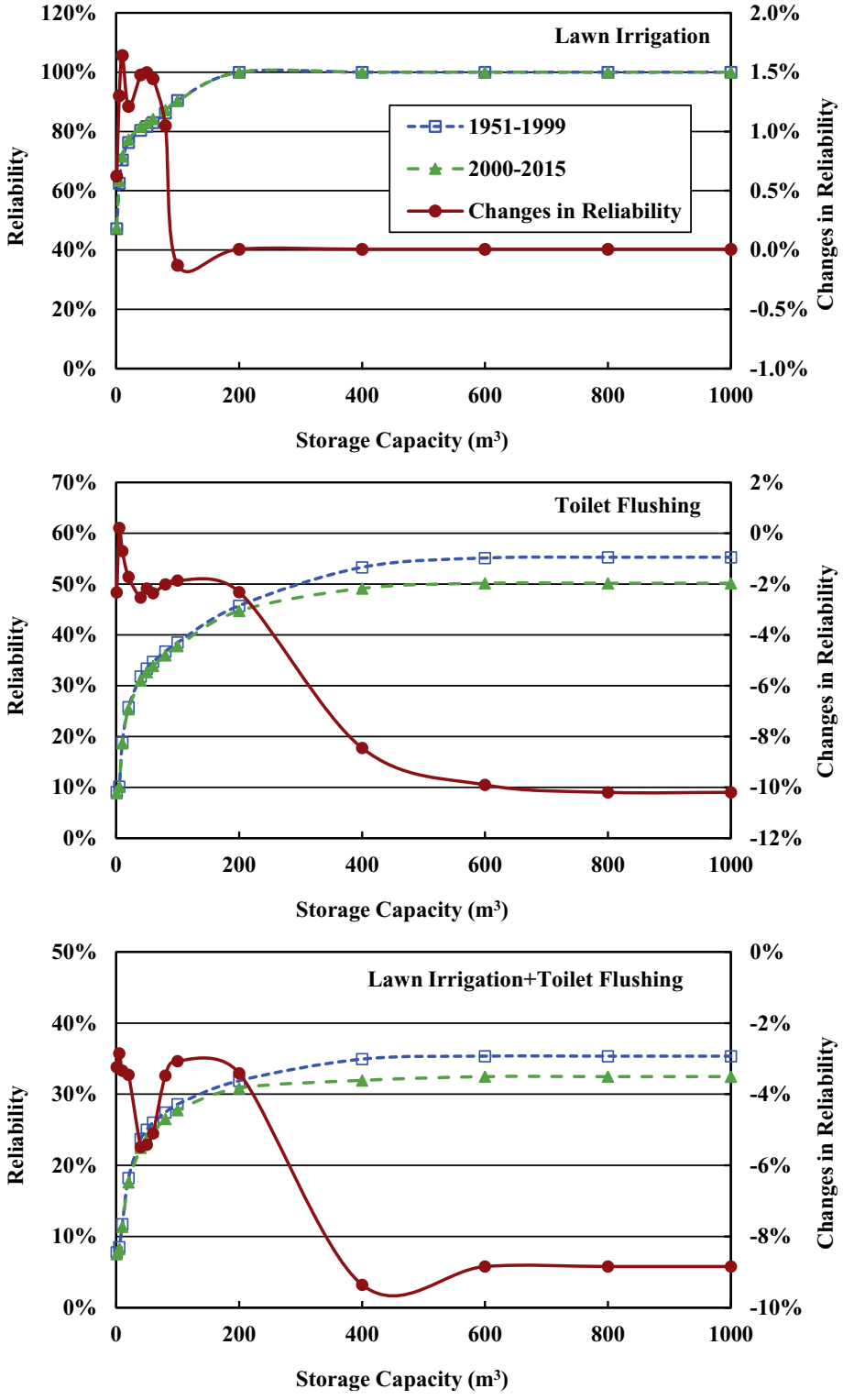

Fig. 9. Changes in reliability of RWH systems at Chengdu.

the corresponding ones in the baseline period (1951–1999). While, at Urumqi, they are all increased by about 22.7% in the changed period compared with the baseline period. At Chengdu, however, the changes in water saving efficiency are dependent on water demand scenarios: larger water demand, more reduction in water saving efficiency. Rainfall change in dry season at the three locations is beneficial for RWH whereas the impacts of rainfall change in wet season on RWH are bidirectional depending on the changing trends of rainfall.

Reliability of RWH systems can be enhanced by the rising trends of rainfall, but impaired by the declining ones. The larger the declining extent of rainfall is or the more the water demand is, the severer the impairment in the achievable reliability could be. In line with the different trends of rainfall change in wet season at the

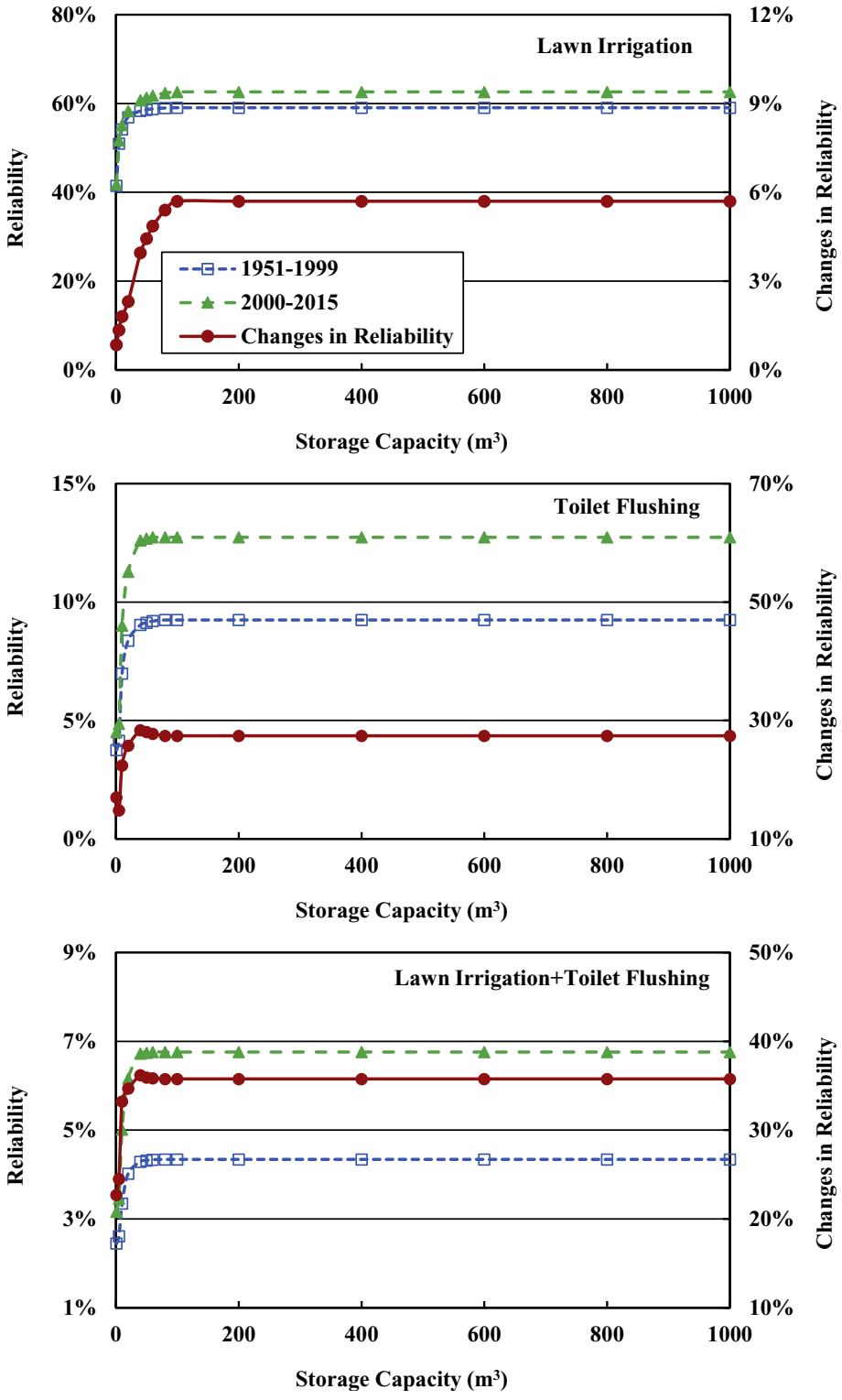

Fig. 10. Changes in reliability of RWH systems at Urumqi.

three locations, reliability of RWH is decreasing at both Beijing and Chengdu (−1.1% to −24.0%), but increasing at Urumqi (23.1%–44.9%). The reliabilities of RWH systems at the three cities are all rising in dry season as all of them are getting more rainfall in dry season.

The findings of this study signify the importance of incorporation of climate change conditions (e.g., rainfall change) in the design and evaluation of RWH systems. The change patterns of water saving efficiency and reliability of RWH at the three locations for the three water demand scenarios indicate that different adaptive and location specific measures can be adopted for RWH to accommodate climate change. At Urumqi where rainfall has an increasing trend, a RWH system with a smaller tank or cistern size could provide the same performance in the changed period.

Table 4
Reliability of 100 m^3 RWH systems in wet and dry seasons at Beijing, Chengdu and Urumqi.

	Wet season			Dry season		
	Baseline period	Changed period	Changes	Baseline period	Changed period	Changes
Lawn Irrigation						
Chengdu	49.7%	49.1%	**−1.1%**	7.9%	8.3%	**5.6%**
Beijing	32.3%	27.8%	**−14.0%**	10.8%	11.0%	**1.1%**
Urumqi	12.7%	15.6%	**23.1%**	13.4%	14.1%	**4.7%**
Toilet Flushing						
Chengdu	36.2%	33.7%	**−6.9%**	2.3%	4.1%	**80.4%**
Beijing	27.4%	24.4%	**−10.8%**	1.6%	2.1%	**36.6%**
Urumqi	6.9%	9.1%	**32.1%**	2.4%	3.6%	**54.2%**
Lawn Irrigation + Toilet Flushing						
Chengdu	26.6%	24.7%	**−7.4%**	2.0%	3.1%	**56.2%**
Beijing	15.2%	11.6%	**−24.0%**	1.0%	1.6%	**54.8%**
Urumqi	2.3%	3.3%	**44.9%**	2.0%	3.4%	**67.8%**

Note: changes in % are the relative differences between the reliability values in the changed and baseline periods.

However, at Beijing and Chengdu where rainfall has a decreasing trend, a higher storage capacity of a RWH system is needed in the changed period. Furthermore, it should be noted that the deceases in the maximum or achievable water saving efficiency and reliability of RWH systems at Beijing and Chengdu could not be simply resolved by using a larger tank or cistern when the rainfall conditions are the limiting factors for the performance of RWH systems. Under this circumstance, adjusting the contributing areas or water demand scenarios of RWH systems could also be considered in the design or evaluation.

Acknowledgements

This work has been supported by the Fundamental Research Funds for the Central Universities (NO. 2015ZCQ-SB-01, YX2015-18, and 2016ZCQ06) and the National Natural Science Foundation of China (NO. 51609004), and the Major Science and Technology Program for Water Pollution Control and Treatment (No. 2017ZX07102-001.

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